Jurnal Elkolind Volume 13, Nomor 1, Mei 2026
DOI: http://dx.doi.org/10.33795/elkolind.v13i1.9705

Performance Evaluation of Fuzzy Logic–Enhanced Perturb and Observe MPPT for Photovoltaic Systems

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Received: 11/04/2023 *Revised: 13/05/2023* *Accepted:14/05/2026*

ABSTRAK

Maximum Power Point Tracking (MPPT) merupakan metode penting untuk mengoptimalkan penyerapan energi pada sistem fotovoltaik (PV) yang dipengaruhi oleh perubahan kondisi lingkungan seperti iradiasi dan temperatur. Algoritma Perturb and Observe (P&O) banyak digunakan karena sederhana, namun memiliki kelemahan berupa osilasi pada kondisi tunak dan respon yang lambat terhadap perubahan kondisi. Penelitian ini mengusulkan peningkatan metode MPPT dengan mengintegrasikan fuzzy logic controller (FLC) pada algoritma P&O untuk menghasilkan step-size adaptif pada pengaturan duty cycle. Sistem dimodelkan dan disimulasikan menggunakan MATLAB/Simulink yang meliputi PV array dan boost converter pada berbagai kondisi operasi, yaitu iradiasi konstan, iradiasi berubah, dan perubahan temperatur. Kinerja metode dibandingkan berdasarkan parameter daya keluaran, ripple tegangan dan arus, efisiensi, serta respon dinamis. Hasil simulasi menunjukkan bahwa metode FLC–P&O mampu mengurangi ripple tegangan dari 5,24% menjadi 2,33% serta mempercepat settling time dari 6,312 ms menjadi 1,872 ms. Oleh karena itu, integrasi logika fuzzy dengan algoritma P&O memberikan solusi yang sederhana namun efektif untuk meningkatkan kinerja MPPT pada sistem panel surya di bawah kondisi lingkungan yang dinamis.

Kata Kunci: Logika Fuzzy, MPPT, *Perturb & Observe*,Panel Surya

ABSTRACT

Maximum Power Point Tracking (MPPT) is a crucial technique to optimize energy extraction in photovoltaic (PV) systems under varying environmental conditions such as irradiance and temperature. The conventional Perturb and Observe (P&O) algorithm is widely used due to its simplicity; however, it suffers from steady-state oscillations and slow response to environmental changes. This study proposes an improved MPPT method by integrating a fuzzy logic controller (FLC) with the conventional P&O algorithm to generate an adaptive step size for duty cycle adjustment. The system is modeled and simulated using MATLAB/Simulink, including a PV array and a boost converter, under different operating conditions such as constant irradiance, varying irradiance, and temperature variations. The performance of both methods is evaluated based on output power, voltage and current ripple, efficiency, and dynamic response. The simulation results show that the proposed FLC–P&O method reduces voltage ripple from 5.24% to 2.33% and improves settling time from 6.312 ms to 1.872 ms. Therefore, the integration of fuzzy logic with the P&O algorithm provides a simple yet effective solution to improve MPPT performance in photovoltaic systems operating under dynamic environmental conditions.

Keywords: *Fuzzy Logic, MPPT, Perturb & Observe, Solar Panel*

1. INTRODUCTION

The increasing global demand for energy, accompanied by rising environmental concerns, has accelerated the development and utilization of renewable energy resources. According to the International Energy Agency, global CO_2 emissions and fossil fuel consumption are expected to increase significantly in the coming decades, leading to severe environmental impacts such as global temperature rise [1]. In this context, photovoltaic (PV)

p-ISSN: 2356-0533; e-ISSN: 2355-9195

systems have emerged as one of the most promising renewable energy technologies due to their ease of installation, low operating cost, and technological maturity [2].

Despite these advantages, PV systems still face several technical challenges, particularly related to their relatively low energy conversion efficiency, which typically ranges from 12% to 26% [3]. Moreover, the output characteristics of PV systems are highly dependent on environmental conditions, especially solar irradiance and temperature. These variations cause nonlinear changes in the current–voltage (I–V) and power–voltage (P–V) characteristics, making it difficult to continuously operate the system at its maximum power point (MPP). Therefore, the implementation of Maximum Power Point Tracking (MPPT) techniques is essential to ensure optimal energy extraction under varying environmental conditions [4].

Various MPPT methods have been developed over the past decades. Conventional techniques such as Perturb and Observe (P&O) and Incremental Conductance are widely adopted due to their simple structure, ease of implementation, and low computational cost [5], [6]. However, these methods suffer from several drawbacks, including steady-state oscillations around the MPP, slow convergence speed, and reduced efficiency under rapidly changing environmental conditions. In particular, the fixed step size used in the conventional P&O algorithm limits its ability to balance between fast dynamic response and minimal steady-state oscillation.

To overcome these limitations, advanced MPPT techniques based on intelligent control methods have been proposed, including fuzzy logic control, particle swarm optimization (PSO), and ant colony optimization (ACO) [7]. Among these approaches, fuzzy logic control (FLC) is widely recognized for its ability to handle nonlinear systems and uncertainties without requiring an accurate mathematical model. By generating an adaptive step size based on system conditions, FLC can improve both transient response and steady-state performance of MPPT algorithms.

This paper proposes an enhanced MPPT method by integrating fuzzy logic control with the conventional P&O algorithm to produce a variable step-size mechanism. The proposed approach aims to reduce steady-state oscillations and improve convergence speed under varying environmental conditions. The system is modeled and simulated in MATLAB/Simulink, incorporating a PV array and a boost converter. The performance of the conventional P&O and the fuzzy logic–enhanced P&O methods is evaluated under different scenarios, including constant irradiance, varying irradiance, and temperature changes. The results are analyzed in terms of output power, ripple characteristics, efficiency, and dynamic response.

This paper is organized into 4 parts, Chapter I is an introduction that explains the background and objectives of the research. Then Chapter 2 is methodology of research that explain the photovoltaic, algorithm modelling, and fuzzy logic controller and whole Simulink modelling of this simulation. Chapter III contains the results and data analysis and closes with Chapter IV which is the conclusion.

2. METHODOLOGY

This study employs a simulation-based approach to evaluate the performance of a fuzzy logic–enhanced Perturb and Observe (FLC–P&O) algorithm for maximum power point tracking (MPPT) in photovoltaic systems. The overall system consists of a photovoltaic (PV) array, a DC–DC boost converter, and an MPPT controller implemented using both conventional P&O and the proposed FLC–P&O methods. The modeling and analysis are carried out using MATLAB/Simulink under various operating conditions, including constant irradiance, varying irradiance, and temperature changes. The system performance is assessed based on key parameters such as output power, voltage and current ripple, efficiency, and dynamic response.

2.1 Photovoltaic modelling and Characteristics

Photovoltaic consists of some solar cell that connected series and parallel to convert power form sun irradiance power to electricity. The combination of some photovoltaic system is called PV array. The modelling of PV array in this paper using block PV array provided in Simulink/MATLAB. he PV Array block implements an array of photovoltaic (PV) modules. The array is built of strings of modules connected in parallel, each string consisting of modules connected in series. In this model, a single PV is represented by a five-parameter model using a light-generated current source (IL), diode, series resistance (Rs), and shunt resistance (Rsh) to represent the irradiance- and temperature-dependent I-V characteristics of the modules as can be seen in Figure 1[8]

p-ISSN: 2356-0533; e-ISSN: 2355-9195

DOI: http://dx.doi.org/10.33795/elkolind.v13i1.9705

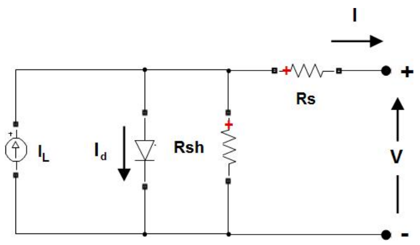

Figure 1 : PV module equivalent circuit

The diode I-V characteristics for a single module are defined by the equations[8]

$$I_d = [\exp\left(\frac{V_d}{V_i}\right) - 1\,] \quad (1)$$

$$V_T = \frac{kT}{q} \times nl \times N_{cell} \quad (2)$$

The PV Array block offers details on five solar PV panels that are wired in series. The solar PV panel utilized was a 315 Wp monocrystalline panel that Zantia sold commercially in Portugal. The specifications of PV can be noticed in Table 1.

TABLE I : MAIN PV CHARACTERISTICS

Parameter	Value	Unit
I_{sc}	9.98	A
V_{oc}	40.80	V
I_{Mpp}	9.45	A
V_{Mpp}	33.35	V
$\%I_{sc}$	0.05	$\%/^0C$
$\%V_{oc}$	-0.29	$\%/^0C$

The I-V and P-V curve characteristics of PV array block that used in simulation can be extracted from Simulink block that shown in Figure 2. The current, voltage and power value in various irradiance can be noticed in graph. The maximum power that can be produced is 1575 Watt when the Voltage is 166.75 Volt. this value is determined as a parameter to calculate the efficiency of MPPT algorithms used in this paper.

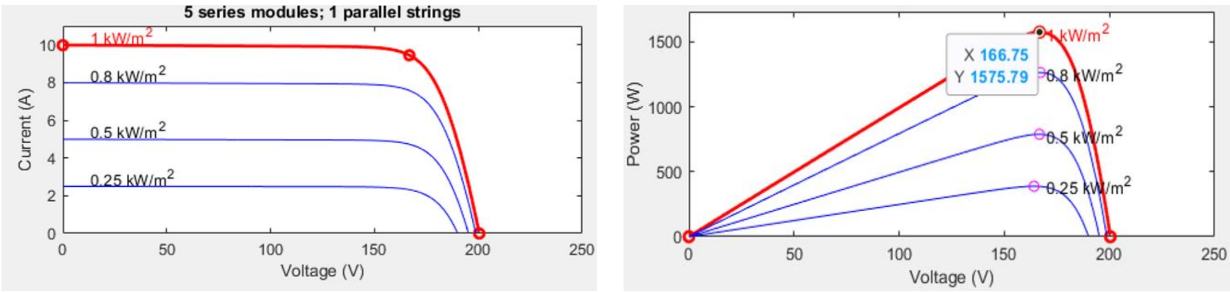

Figure 2 PV array block characteristics

2.2 Boost Converter Design

The boost converter is one of DC-DC converter that produces an output voltage that is greater than or equal to the input voltage. Figure 3 shows the basic circuit of boost converter. This utilizes another switching converter that operates by periodically opening and closing an electronic switch. The basic circuit consists of Inductor, diode, MOSFET, capacitor and load.

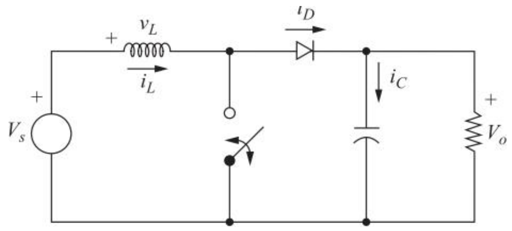

Figure 3 Basic circuit of boost converter[9]

Due to the changing input voltage from photovoltaic depending on irradiation of sun, the basic circuit above need an additional capacitor. This capacitor is placed parallel to the MOSFET to increase the stability of the input voltage to boost converter. Figure 4 boost converter circuit illustrates the boost converter that used in this simulation [4].

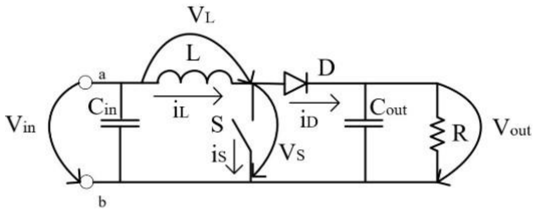

Figure 4 boost converter circuit

In the boost converters, the output voltage and input voltage, depends on the duty cycle (D) value, as can be seen in Equation 3. While another parameter of boost converter can be calculated according to reference[4]. Where D represents duty cycle, f is frequency switching of MOSFET, ΔV is ripple voltage and r is the ratio of the current ripple given by the division between the current variation and the medium value of the inductor current. From those equations, the calculated values for each parameter can be seen in Table 2

$$C_{in} = \frac{I_{out}.r}{8rf\,\Delta V(1-D)} \quad (3)$$

$$C_{out} = \frac{I_{out}.(1-D)}{f\,\Delta V} \quad (4)$$

$$L = \frac{V_{out}D(1-D)^2}{I_{out}rf} \quad (5)$$

TABLE II : BOOST CONVERTER PARAMETER

Parameter	Value	Unit
C_{in}	10	mF
C_{out}	5	μF
L	9.45	mH
f	20	KHz
D	0.8	-

2.3 Conventional P&O Algorithm Design

The P&O method's basic principles are built on perturbing and shifting the solar PV system's set point in relation to the sign of the system's previous gain in power. The same and opposite directions of applying the perturbation depend on the rise and fall in the PV output respectively. The conventional P&O algorithm track the MPP based on slope of dP/dV on P-V curve continuously. If the value of this slope is zero, it means that the MPP is reached. If this slope greater than zero, the duty cycle will be decrease. In contrast, the negative value of this slope will decrease the duty cycle by reduce it with step size ΔD . The flowchart concept of conventional P&O depict in Figure 5 [10] and the MPP tracking by decreasing or increasing duty cycle shown in Figure 6 [11].

p-ISSN: 2356-0533; e-ISSN: 2355-9195

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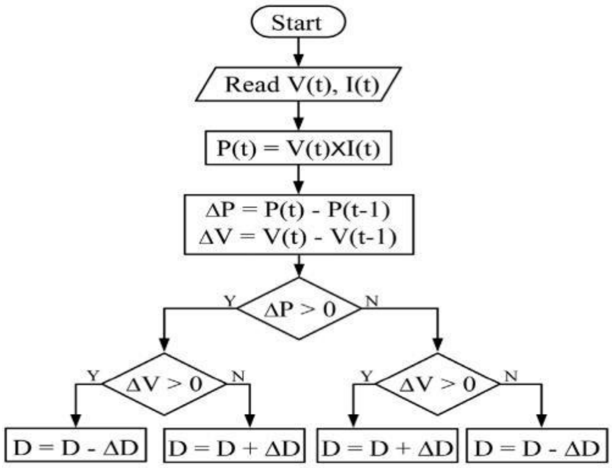

Figure 5 Flowchart of conventional P&O algorithm

The drawback of this method is that, up until the operation is complete, the power output starts to vary across the MPP with a set step-size. This strategy would fail to produce a steady MPP, and power losses would rise as a result. Choosing a greater step-size can produce a rapid response, but at the expense of having higher power losses, it should be noted. In contrast, adopting smaller step size values causes a slower reaction but with less power loss . A variable step-size P&O approach may be used to properly solve each of these shortcomings [11].

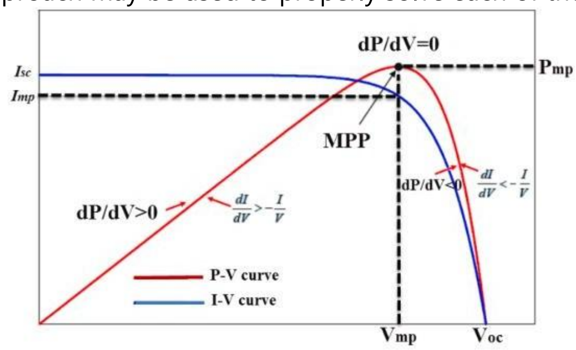

Figure 6 PV MPPT tracking by changing duty cycle

2.4 Fuzzy Logic – Perturb and Observe

Fuzzy logic was proposed by Lofti Zadeh in 1965 [12], this type of mathematical logic pretends to emulate the human inference process handling certain amount of constant uncertainty. In processing the fuzzy system, the input must be a membership function or a linguistic variable. The fuzzy membership function describes the membership status of a value on the variable. Mathematically this process can be represented as follows [13]

$$A = [(x, \mu_A(x)|x \in X] \quad (6)$$

A logical system consists of several interrelated processes. The processes that occur in fuzzy logic can be seen in the following flow chart. To enhanced the P&O algorithm in MPPT system, fuzzy produce a variable step-size duty cycle according the error of slope dP/dV. These steps and the general architecture of the controller are presented in Figure 7.

p-ISSN: 2356-0533; e-ISSN: 2355-9195

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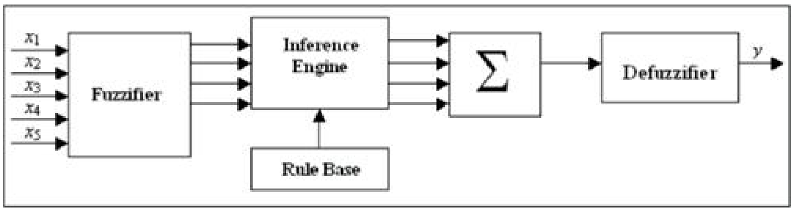


Figure 7 Fuzzy Logic system flowchart

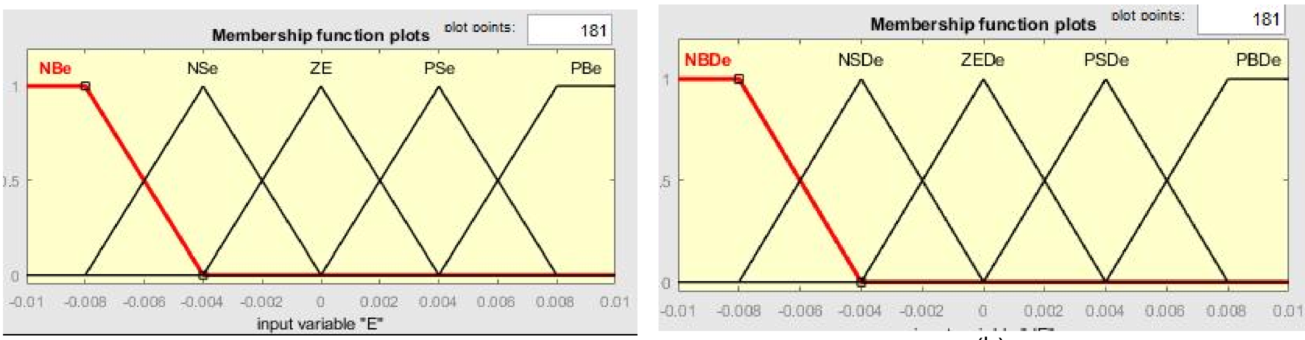
1. Fuzzification

Fuzzification process is a process to change the input in the form of non-fuzzy variables (numeric variables) into fuzzy variables. The input of this algorithm is the error and delta error of the slope dP/dV. Error defines the difference value between current measurement and previous measurements. While delta error defines the difference of error with previous measurements. Mathematically can be written in equation 7 and 8.

$$E(t) = \frac{P(t)-P(t-1)}{V(t)-V(t-1)} \qquad (7)$$

$$dE = E(t) - E(t-1) \qquad (8)$$

This value will be converted to membership function in order to be processed by fuzzy controlled. The values of the membership function are assigned to the linguistic variables, using five fuzzy subsets: NB (Negative Big), NS (Negative Small), ZE (Zero), PS (Positive Small), PB (Positive Big). The shape of the membership function and the partition of the fuzzy subsets, which can be adapted to appropriate the system, are shown in Figure 8. Figure 9 Input delta error membership function. While the output of FLC is the variable step-size od duty cycle. The output should be converted to membership function that can be shown in Figure 10.



(a) (b)

Figure 8 : membership function input of fuzzy logic. (a) error input membership function (b) delta error input membership function

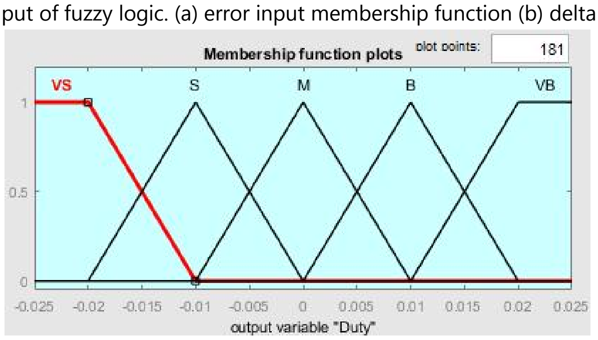


Figure 9 Variable step-size duty cycle membership function

p-ISSN: 2356-0533; e-ISSN: 2355-9195

2. Fuzzy Inference System

At this process the system inference of the input value to determine the output value as a form of decision maker. The three most widely used inference methods are the Mamdani, Sugeno, and Tsukamoto inference methods. In this research the mamdani inference system is applied to examine the duty cycle output due to the capacity to handle imprecise inputs through linguistic variables and predefined rules, facilitating decision-making under uncertainty.

3. Fuzzy Rule Base

Fuzzy rule base is the basic rule used in fuzzy logic. The basic rule in fuzzy logic uses the implication form "if...then...". The basic rules are determined with the help of an expert who knows the characteristics of the object to be controlled. In this simulation the rule base that was designed depict in Figure. The rule base is determined by the characteristic of P&O algorithms that the duty cycle will be decreased if the error is big and vice versa.

4. Defuzzification

The next stage is defuzzification, which involves modifying the fuzzy output values with their membership function, resulting in Crisp Outputs. The center of gravity approach was utilized for this system's defuzzification, resulting in the output duty cycle.

TABLE III : BOOST CONVERTER PARAMETER

Error \ Delta Error	NB	NS	Ze	PS	PB
NB	NB	NB	NB	NS	Ze
NS	NB	NS	NS	Ze	Ze
Ze	NS	NS	Ze	PS	PS
PS	Ze	Ze	PS	PS	PB
PB	Ze	PS	PB	PB	PB

2.5 SIMULINK MODELLING OF PROPOSED SYSTEM

Figure 11 depicts a complete model of MPPT based on a traditional P&O and fuzzy logic-P&O including photovoltaic array, boost converter circuit, variation of temperature and irradiation, and the measurement system. The performance of both algorithms will be compared during various environmental changes.

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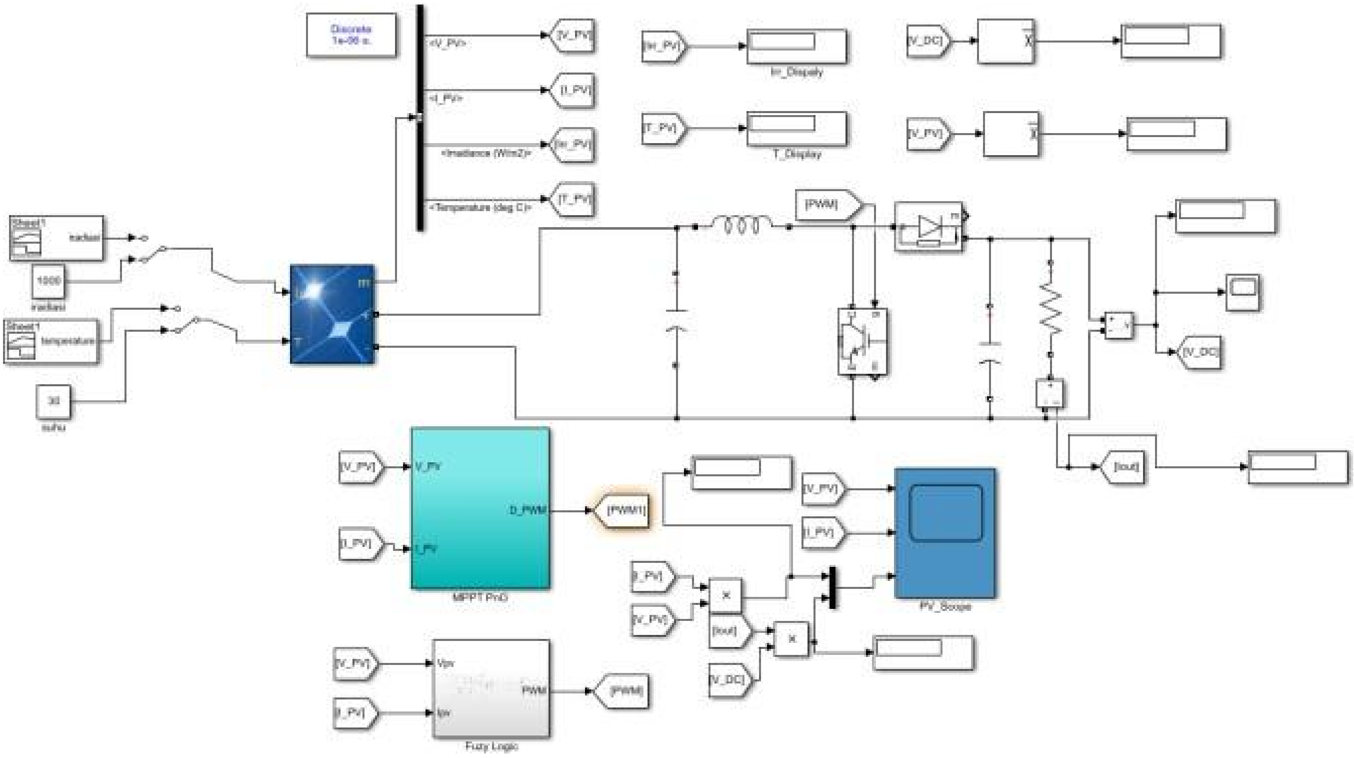


Figure 10 Simulink modelling of proposed system

According to P&O concept that explained before in Figure 6, the algorithm is modelled based the logic of P&O algorithm. The modelling use the function block that provided by Simulink. The input of the block is Voltage and current from photovoltaic that will be calculated using P&O traditional logic that can be seen in Figure 14.

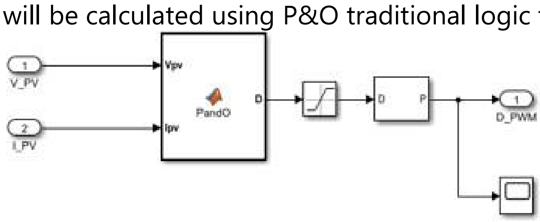


Figure 11 Simulink modelling of proposed system

The modelling of fuzzy logic controller to create adaptive size-step of P&O depict in Figure 15. The logic of P&O firstly is represented by some blocks provide in Simulink library which the input is photovoltaic current and voltage. from both variables will be calculated the error slope dP/dV that will be inputted to fuzzy logic controller. The output of FLC is step- size of duty cycle that will be added or subtracted by initial duty cycle. The total duty cycle will be converted to PWM signal that will be inputted to the MOSFET gate.

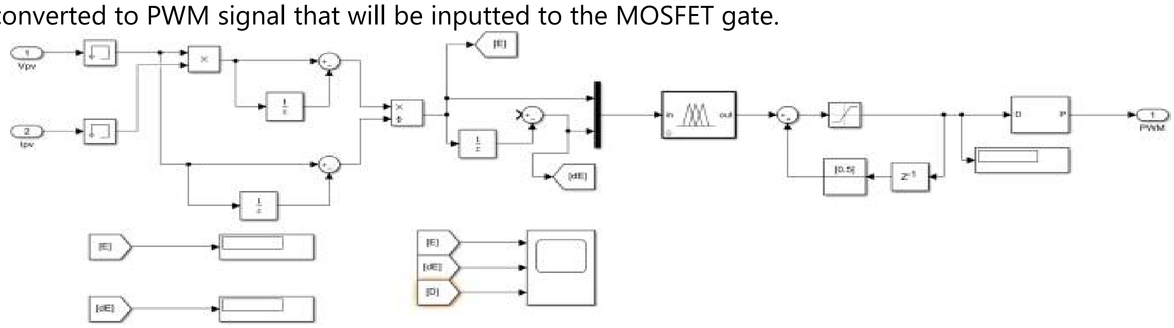


Figure 12 fuzzy logic-P&O modelling

p-ISSN: 2356-0533; e-ISSN: 2355-9195

DOI: http://dx.doi.org/10.33795/elkolind.v13i1.9705

3. RESULT AND DISCUSSION

The performance of the conventional Perturb and Observe (P&O) and the fuzzy logic–enhanced P&O (FLC–P&O) algorithms is evaluated under three operating condnitions, namely constant irradiance, varying irradiance, and temperature changes. The comparison focuses on both steady-state and dynamic performance, including output power, ripple characteristics, efficiency, and response time.

3.1 Simulation Under Constant Irradiation

Under constant irradiance conditions (1000 W/m² and 25°C), both algorithms are able to track the maximum power point with comparable accuracy, as shown in Figure 16(c). The output power produced by the conventional P&O and FLC–P&O methods are 1534 W and 1542 W, respectively, as summarized in Table 4. This corresponds to a slight efficiency improvement from 97.4% to 97.9%. The voltage and current profiles in Figure 16(a) and Figure 16(b) further confirm that both methods operate close to the optimal point. However, significant differences are observed in the dynamic response. Based on Table 4, the FLC–P&O method reduces the voltage ripple from 5.24% to 2.33% and the current ripple from 6.08% to 2.68%, which is also visually reflected in the smoother waveform in Figure 16(a) and Figure 16(b). Additionally, the settling time is improved from 6.312 ms to 1.872 ms, indicating faster convergence to the maximum power point.

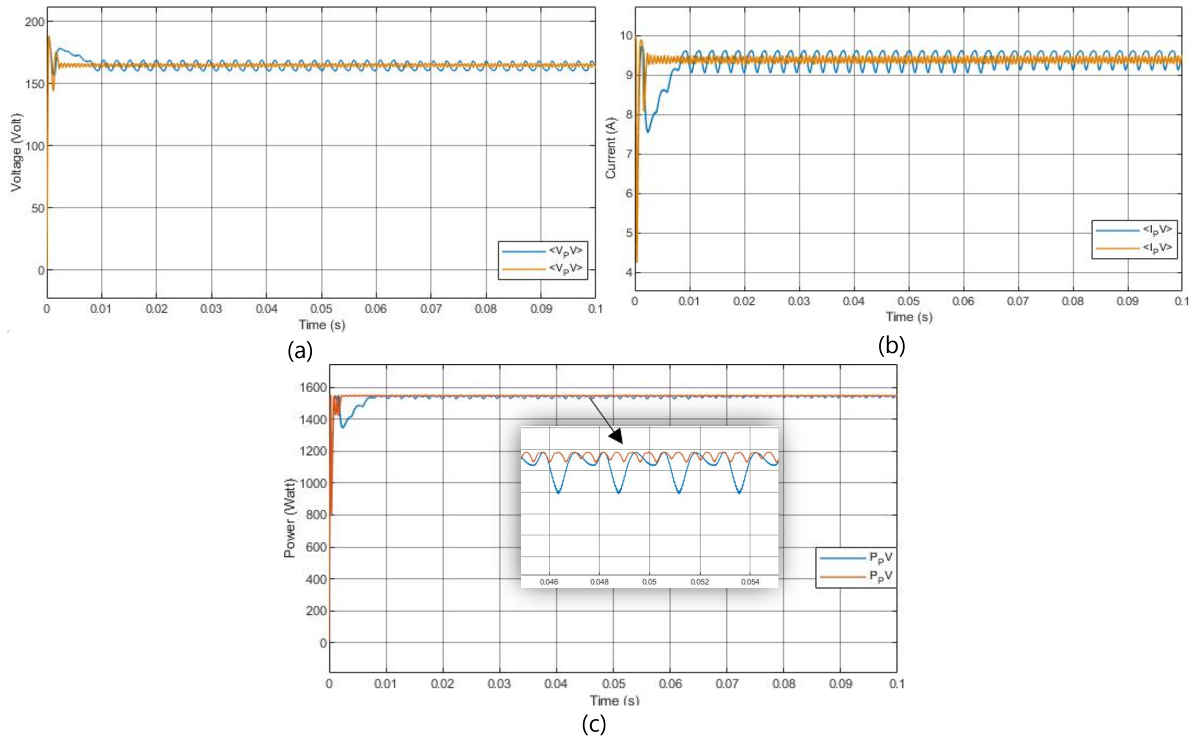


Figure 16 : Simulation results under constant irradiance conditions (1000 W/m², 25°C): (a) Output voltage waveform, (b) Output current waveform. (c) Output power comparison.

This improvement is primarily due to the adaptive step-size mechanism introduced by the fuzzy logic controller. In the conventional P&O method, the fixed step size results in continuous perturbation around the maximum power point, causing oscillations as observed in Figure 16(c). In contrast, the FLC–P&O dynamically adjusts the step size based on the error and change of error of the power-voltage slope, enabling faster convergence and reduced oscillatory behavior.

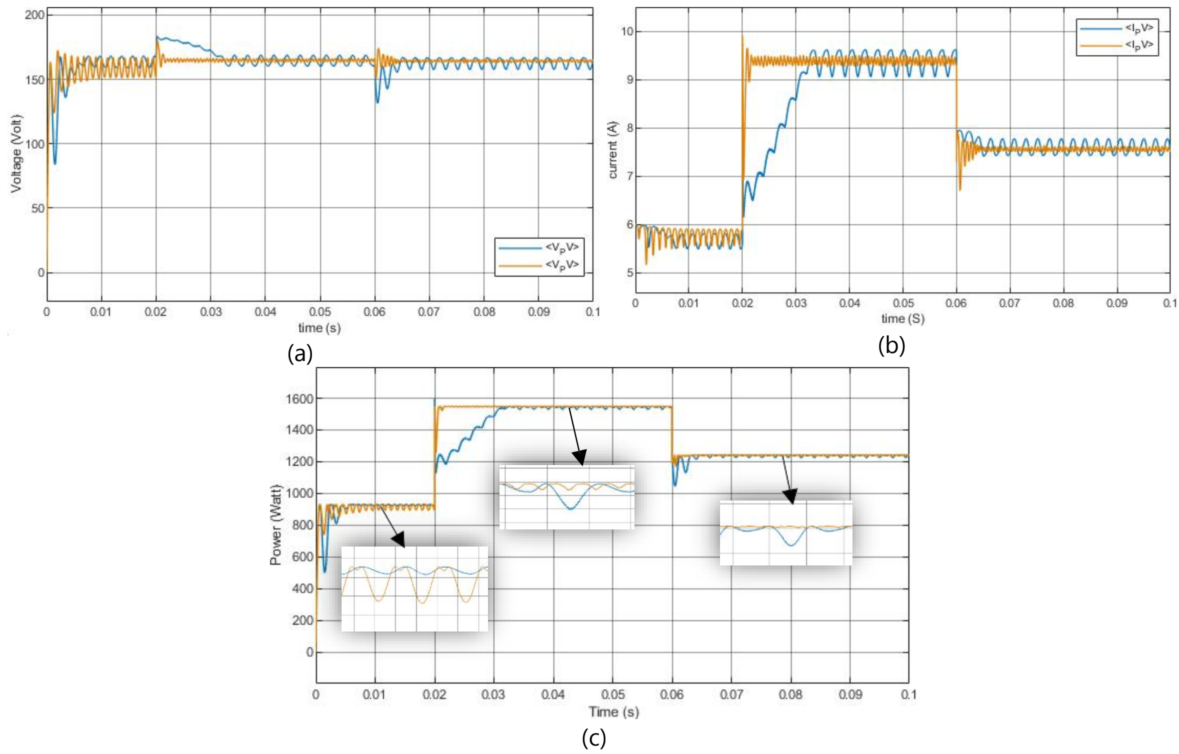
p-ISSN: 2356-0533; e-ISSN: 2355-9195

TABLE IV : PERFORMANCE COMPARISON BETWEEN CONVENTIONAL P&O AND FUZZY LOGIC–ENHANCED P&O (FLC–P&O) UNDER CONSTANT IRRADIANCE CONDITIONS

Parameter	P&O	Fuzzy_P&O	Unit
Average Voltage	164.5	164.7	Volt
Average Current	9.33	9.36	Ampere
Ripple Voltage	5.24	2.33	%
Ripple Current	6.08	2.68	%
Average Power	1534	1542	Watt
Efficiency	97.4%	97.9%	-
Rise Time	198	198	microsecond
Settling time	6.312	1.872	milisecond
Max Overshoot	0.50%	0.5	%

3.2 Simulation with variation of irradiance

Under varying irradiance conditions, the system response is illustrated in Figure 17(a)–(c). Both algorithms maintain high efficiency levels above 95%, as reported in Table 5, indicating their capability to track the maximum power point under dynamic environmental conditions. However, the transient response of the conventional P&O method is slower, particularly during rapid changes in irradiance, which can be observed from the delayed stabilization in Figure 17(c). The FLC–P&O method demonstrates faster adaptation and reduced oscillations, resulting in a smoother transition in both voltage and current as shown in Figure 17(a) and Figure 17(b).



(a) (b) (c)

Figure 16 : Simulation results under varying irradiance conditions:, (a) Output voltage waveform, (b) Output current waveform, (c) Output power response

An exception occurs at an irradiance level of 600 W/m², where the ripple voltage of the FLC–P&O method is higher than that of the conventional P&O, as indicated in Table 5. This behavior is also reflected in the waveform fluctuations in Figure 17(a). This condition suggests that the performance of the fuzzy logic controller is sensitive to

 p-ISSN: 2356-0533; e-ISSN: 2355-9195

Jurnal Elkolind Volume 13, Nomor 1, Mei 2026
DOI: http://dx.doi.org/10.33795/elkolind.v13i1.9705

the design of membership functions and rule base, particularly under low irradiance conditions. Therefore, further tuning of the fuzzy parameters may improve performance consistency.

TABLE V : PERFORMANCE COMPARISON OF CONVENTIONAL P&O AND FLC–P&O UNDER VARYING IRRADIANCE CONDITIONS.

(a) Conventional P&O						
Irradiance (W/m^2)	**Voltage (Volt)**	**Current (A)**	**Voltage Ripple (%)**	**Ripple Current (%)**	**Power (Watt)**	**Efficiency(%)**
600	163.60	5.67	5.72	5.80	927.10	97.90
1000	164.50	9.33	5.24	6.08	1534	97.40
800	163.10	7.58	5.64	4.72	1237	97.94
(b) FLC-P&O						
Irradiance (W/m^2)	**Voltage (Volt)**	**Current (A)**	**Voltage Ripple (%)**	**Ripple Current (%)**	**Power (Watt)**	**Efficiency(%)**
600	157.90	5.79	10.77	6.49	915	96.61
1000	164.70	9.36	2.33	2.68	1542	97.90
800	164.30	7.55	1.75	1.76	1242	98.34

3.3 Simulation under change of temperature

The change in temperature is applied to the system to observe the influence of this variable to performance of designed MPPT. The temperature profile change from 25 ^0C to 35 ^0C. The simulation results of these conditions is illustrated in Figure 18 that shows the power, voltage and current of the photovoltaic during the simulation. Both methods exhibit a similar trend where an increase in temperature leads to a reduction in output power, as shown in Figure 18(c), primarily due to the decrease in the open-circuit voltage of the photovoltaic module. The voltage reduction can also be observed in Figure 18(a), while the current variation remains relatively small as shown in Figure 18(b). The difference between the two methods in this scenario is minimal, indicating that temperature variation has a limited impact on the comparative performance of the MPPT algorithms. However, the FLC–P&O still provides slightly smoother responses with reduced ripple.

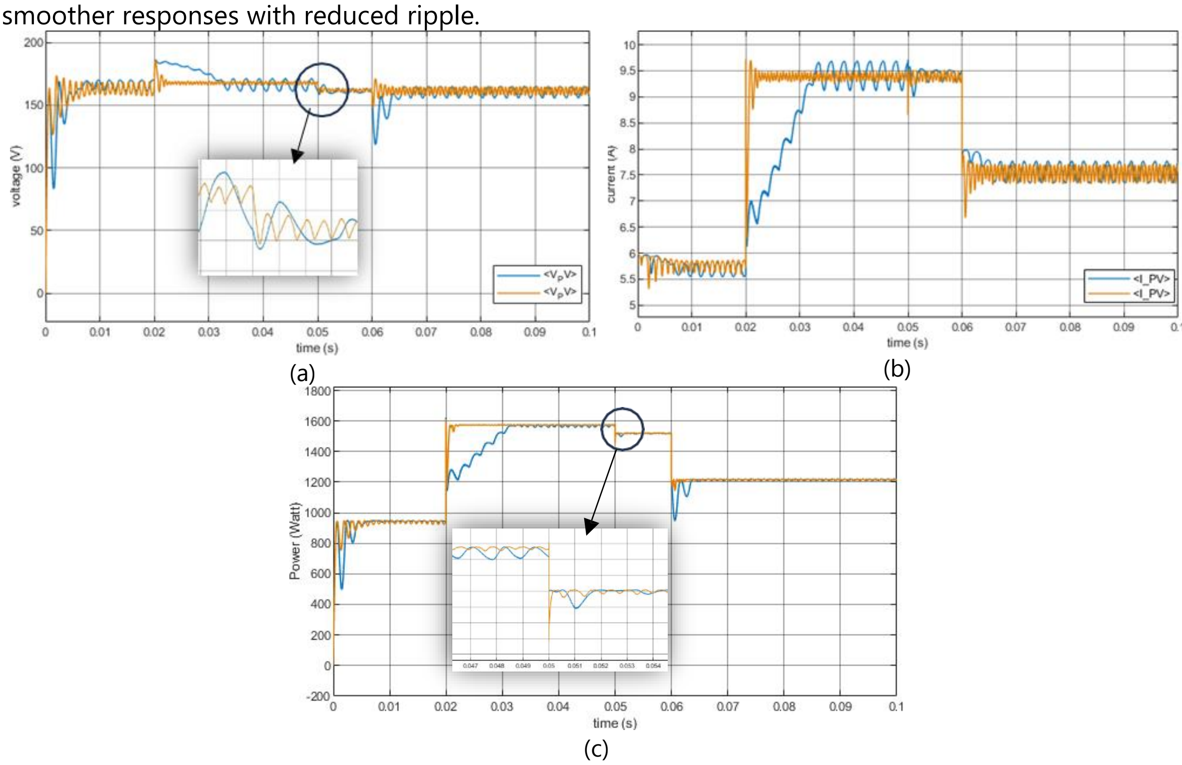


Figure 18 : Simulation results under temperature variation:, (a) Output voltage waveform, (b) Output current waveform, (c) Output power response

4. CONCLUSION

This paper presented a fuzzy logic–enhanced Perturb and Observe (FLC–P&O) algorithm to improve maximum power point tracking (MPPT) in photovoltaic systems. The proposed method introduces an adaptive step-size mechanism to reduce oscillations and improve dynamic response compared to the conventional P&O algorithm. Simulation results show that both methods achieve high efficiency under various conditions. However, the FLC–P&O method provides better dynamic performance, reducing voltage ripple from 5.24% to 2.33%, current ripple from 6.08% to 2.68%, and settling time from 6.312 ms to 1.872 ms. Under varying irradiance, the proposed method demonstrates faster response and improved stability, although its performance is slightly affected at low irradiance levels. Temperature changes have a similar impact on both methods. Overall, the FLC–P&O algorithm improves system stability and response speed with minimal complexity, making it suitable for practical PV applications. Future work will focus on optimizing the fuzzy controller and validating the system experimentally under more complex conditions.

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p-ISSN: 2356-0533; e-ISSN: 2355-9195
9772356053009